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Rice husk ash and imidazole application enhances silicon availability to rice plants and reduces yellow stem borer damage

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ABSTRACT

Silicon (Si) has been implicated to reduce damage by rice pests. In this study we validate the field efficacy of rice husk ash (RHA) and imidazole, alone and in combination, against damage by yellow stem borer (YSB) under field conditions for two seasons in five rice cultivars. Field application of RHA and imidazole, either alone or in combination, enhanced Si deposition (43–59.8 mg g^{-1}) in stem tissues of rice plants as compared to untreated control (30.2 mg g^{-1}). Deposited Si caused significant wearing of mandible incisors, and lowered larval density, thereby decreasing YSB damage and increasing the grain yield significantly. RHA and imidazole did not alter the total sugars and total phenol content in rice cultivars. Field application of imidazole along with RHA at vegetative phase and again at booting stage was on par with insecticidal treatment (carbofuran 3G) with respect to per cent damage, larval density and grain yield. The B: C ratio in the Si treatments varied from 1.16 to 1.31 and T4-RHA + imidazole (applied twice) was at par with one granular insecticide application (1.32) but higher than the untreated control (1.0). RHA and imidazole can be integrated as one of the eco-friendly components in the present scenario of climate change for the management of YSB in rice.

1. Introduction

Yellow stem borer (YSB), *Scirpophaga incertulas* (Walker) (Lepidoptera: Crambidae), is a monophagous insect and one of the most important pest of Asia and South East Asia (Khan et al., 1991). Larvae of this insect infest the rice crop throughout the crop growth stage (Bandong and Litsinger, 2005). When the larvae infest the crop from nursery to tillering stage (vegetative phase), the growing shoots dry up and they can be easily pulled out. This symptom is commonly called as 'dead hearts'. During heading stage (in reproductive phase), attack by the larvae leads to unfilled panicles commonly known as 'white heads'. Depending on the crop stage that is attacked, the grain yield losses may vary from 10 to 90% (Muralidharan and Pasalu, 2006). The yellow stem borer larvae are exposed to the outside environment from the time they hatch from the egg mass to their entry into the stems of rice plant which is usually a few hours. Therefore, control of this insect is difficult because of its cryptic behavior. Hence, there is a need to search for alternative sustainable strategies to manage this pest.

Si is known to induce defense mechanisms like in leaf scald by reducing malonaldehyde concentration, lignin concentration and total soluble phenolics with greater activities of phenyl ammonia lyase (PAL), peroxidase (POD), polyphenol oxidize (PPO) and lipoxygenase (LOX) (Tatagiba et al., 2014). Induced responses in rice appear to vary in response to damage by different pest species. Chewing damage caused by armyworm or cluster caterpillars, *Spodoptera litura* (Fabricus) (Lepidoptera: Noctuidae), caused signal cascades and expression of genes normally associated with induced resistance against herbivores, such as the jasmonic acid (JA) pathway, phenyl propanoid pathway and terpene biosynthesis (Xu et al., 2003) suggesting that the JA signaling pathway in rice is involved in induced resistance against caterpillars. But on the contrary, Duan et al. (2014) reported that salicylic acid (SA) signaling pathway was activated in the resistant rice variety, Kasalath in response to small brown planthopper (SBPH) infestation and the activities of the defense enzymes PAL, POD, and PPO increased remarkably and PAL gene played a considerable role in imparting resistance to SBPH.

In addition to phenols, Si application has proved to impart resistance to rice insect pests *viz*., African striped borer (Ukwungwu, 1984); yellow rice borer (Panda et al., 1975); striped stem borer (Sasamoto, 1958); brown planthopper (Yoshihara et al., 1979;

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Wenqiang et al., 2015); leaf folder (Han et al., 2015). Most of the sources of Si are insoluble and not available to plant as its uptake is in the form of soluble monosilicic acid (Lindsay, 1979). Si can be applied as many inorganic forms such as sodium silicate (Na_2SiO_3), potassium silicate (K_2SiO_3) and calcium silicate (Moraes et al., 2004; McCray et al., 2011) and organic source like rice husk ash (RHA) (Sawant et al., 1994) for insect pest control though dissolution rates vary for different Si sources (Savant et al., 1997). For rice production entirely relying on release of H SiO_4 from amorphous silica as its Si source, the supply of plant-available Si is expected to be exhausted after 5 years of continuous cultivation (Desplanques et al., 2006). It was suggested that the decline in yields of rice grown in many areas of the world was associated with soil depletion of plant-available Si (Savant et al., 1997). This may pose further problems in soils with large fractions of quartz sand, high organic matter content, and characterized as highly weathered, leached, acidic, and low in base saturation (Datnoff et al., 1997). The replenishment of plant-available Si in soil solution is critical and may be characterized based on soil Si dissolution kinetics and Si release from organic sources, including crop residues and burned rice husk. Babu et al. (2014) pointed out that the release of H SiO_4 into soil solution is critical for the amount of plant-available Si and is influenced by different processes (e.g., desorption, polymerization) and soil properties other than pH. This phenomenon explains the unexpected response of rice to Si grown on soil despite high initial Si level and clay content. Therefore, Si fertilization could be important and can be decided based on the soil's ability to replenish the Si removed by plants from the soil solution, especially for soils under continuous, intensive farming systems. A soil's clay content, pH, organic matter content, and Al and Fe oxide content are essential factors to consider when making a recommendation for a Si fertilizer. Hence it is appropriate to apply a material that is rich in Si and also soluble. Therefore in the present study, we have chosen two products RHA which is rich in Si and imidazole which is a proven Si solubiliser and carrier to study their effect on yellow stem borer damage.

RHA is one of the byproducts of rice milling and is a huge source of Si and K with high specific surface which plays an important role in soil stabilization and has long term positive effects (Brenda et al., 2016). RHA, a potential available form of Si (Prakash et al., 2007) is easily available and less expensive. Sawant et al. (1994) reported that the application of black to grey RHA at 0.5–1.0 kg m^{-2} to rice nursery resulted in healthy and strong seedlings that were tolerant to stem borer attack. Application of Si solubilisers such as simple amino acids which proved to be cost effective, reduced damage by yellow stem borer and blast (*Pyricularia grisea*) (Ranganathan et al., 2006; Voleti et al., 2008). Among the simple amino acids, imidazole ($C_3H_4N_2$), an organic, aromatic heterocyclic compound was found to be effective and promoted the equilibrium in favour of silicic acid by a dual mechanism involving Si hydrolysis and its subsequent stabilization by hydrogen bonding (Voleti et al., 2009; Ranganathan et al., 2011). In our recent study under greenhouse conditions, we demonstrated that application of RHA + Imidazole resulted in reduced yellow stem borer damage due to 1) increased mandible wear 2) larval mortality and 3) abrasion in larval midgut epithelium (Jeer et al., 2016). In this paper, we report the field efficacy of rice husk ash and imidazole alone, and in combination, for minimizing YSB damage.

2. Materials and methods

2.1. Experimental site

Field experiments were carried out for two seasons at ICAR-Indian Institute of Rice Research (IIRR), Rajendranagar, Hyderabad, India (17°19′N and of 78° 24′ E, 542 MSL) during 2011–2012. The soils were clayey, slightly alkaline (pH 8.1), non saline, medium in organic carbon content with, 225 kg/ha available N, 75–80 kg/ha available P_2O_5 and > 500 kg/ha K_2O.

2.2. Experimental procedure

Field trials were laid out to study the efficacy of Si sources *i.e.* Rice husk ash (RHA) and silicon solubiliser cum carrier *i.e.* imidazole (Chemical formula: $C_3H_4N_2$, Mol. Wt – 68.08; Hi-Pure fine Chem. Industries, Chennai, India) on silicon deposition, incidence and damage by YSB, *S. incertulas* in selected rice cultivars during dry season, 2011–12 and wet season, 2012. The experiment was planned in split-plot design with five rice cultivars as main treatments and different doses of RHA and imidazole as subplot treatments with four replications. Cultivars were BPT 5204, MTU 1010, KRH 2, Vandana and Pusa Basmati (PB) 1, which are the most popular and commonly grown rice varieties/hybrids in India. Si sources as treatments included only RHA (T1), only imidazole (T2), RHA + imidazole applied once at maximum tillering (MT) stage (T3), RHA + imidazole applied at MT and another dose of imidazole alone at booting stage (T4), carbofuran 3G applied at 33 kg/ha during MT stage (T5) and an untreated control (T6.) The crop was raised as per the recommended package of practices except for crop protection measures with an individual plot size of 7.2 m^2. Based on the solubility of Si by imidazole, 40.8 g/ha/application of imidazole and RHA equivalent to 85 mg of Si m^{-2} $application^{-1}$ was applied to the soil (Jeer et al., 2016).

2.3. Preparation of Rice husk ash

Rice husk was collected from a single source, burnt to grey black color in earthen pots, powdered and sieved through a fine mesh (60 mesh). Grayish black colored ash was collected and used for all the studies. The quantification of Si present in RHA was carried out by molybdenum yellow method (Saito et al., 2005).

2.4. Soil application of Si

Before imposing the treatments, the plant samples were collected from all the plots for analysis of initial Si content, total sugars and total phenols in stem tissues. All the treatments were imposed in individual plots at 30 days after transplanting (DAT) by dissolving in a small quantity of water for proper distribution (Jeer et al., 2016). In T4 treatment, a second dose of imidazole was applied at booting stage. Booting stage varied with the duration of the variety.

2.5. Field efficacy studies

Field incidence of YSB was recorded as total number of dead hearts and total number of healthy tillers in 10 randomly selected hills per replication at 45 and 60 days after transplanting (DAT). Similarly, total number of white ears and total number of panicle bearing tillers were recorded at harvest. Per cent dead hearts and per cent white heads were calculated as follows:

$$\text{Percent dead hearts} = \frac{\text{Total number of dead hearts}}{\text{Total number of tillers}} \times 100$$

$$\text{Percent white heads} = \frac{\text{Total number of white heads}}{\text{Total number of panicle bearing tillers}} \times 100$$

Grain yield was recorded on net plot basis by leaving one border row on all sides of each plot.

2.6. Larval density

From each replication of a treatment in the field, a sub sample of four infested rice plants were uprooted separately, dissected and observed for total number of YSB larvae. From each treatment eight larvae were preserved in 70% ethyl alcohol for mandible studies.

2.7. Mandible measurements

The studies on wearing of mandibles in larval instars were carried out to observe the erosion of mandibles due to the feeding on Si treated rice plants by measuring the length of the incisors as reported earlier (Jeer et al., 2016).

2.8. Estimation of biochemical parameters

Stem tissues (length of 10 cm from the base of the plant) were sampled from each treatment one day before application of Si (1DBA), seven days after application of treatment (7DAA) and one week after imposition of second dose of imidazole in T4 treatment at booting stage (7DAB). The samples were oven dried at 60 °C for 48 h, powdered and used for estimation of biochemical parameters *viz.*, total Si (Saito et al., 2005), total sugars content (Dubois et al., 1956) and total phenol content (Malick and Singh, 1980).

2.9. Economic analysis

Benefit cost analysis was carried out for all the treatments and the following relations were used for calculating benefit cost ratios. Costs (T1) = costs of (land preparation + nursery bed preparation + nursery bed maintenance + nursery pulling and transport + fertilizer application + transplanting + rice husk procurement and rice husk ash preparation + irrigation + Weeding + Harvesting + Threshing + Labor for treatment imposition); Costs (T2) = Cost (T1-Rice husk procurement and rice husk ash preparation) + costs of (imidazole); Costs (T3) = Cost (T1) + costs of (imidazole + labor); Costs (T4) = Cost (T3) + costs of (imidazole + labor); Costs (T5) = Cost (T1-Rice husk procurement and rice husk ash preparation) + costs of (carbofuran); Costs (T6) = Cost (T1-(Rice husk procurement and rice husk ash preparation + Labor for treatment imposition)). Net income (INR ha^{-1}) = Grain yield × Price of grain-Costs. Benefit: Cost (B: C) ratio was calculated according to Meng et al. (2012) with some modifications.

$$\text{B: C} = \frac{\text{Gross returns from treatment}}{\text{Cost of treatment}}$$

2.10. Statistical analysis

Percentage damage data from field experiments were arcsine transformed before analysis. General linear model (GLM) procedure was used for all the experimental analyses in SAS® 9.2 (SAS, 2003) using three-way Analysis of Variance (ANOVA). Tukey's Honestly Significant Difference (HSD) test ($\alpha = 0.05$) was performed for all multiple mean comparisons.

3. Results

3.1. Field efficacy studies

In wet season, infestation of yellow stem borer was significantly high than in dry season. Correspondingly the number of deadhearts and white heads was high and grain yield was lower than in the dry season (Table 1). Dead heart damage, white head damage, larval density and grain yield were highly significant across Si treatments. Varieties alone had significant effect on the level of infestation and grain yield. The interaction effects *viz.*, season × variety, season × treatment, variety × treatment and season × variety × treatment were not significant (Table 1).

Dead heart damage: The dead heart damage was significantly high in wet season (10.1–13.7%) as compared to dry season (7.9–11.9%) at both 45 DAT and 60 DAT. All the Si treatments had significantly less dead heart and white head damage as compared to untreated control. Dead hearts damage (%) varied significantly among silicon sources at 45 DAT (7.3–9.5%) and 60 DAT (9.4–12.9%) as compared to the untreated control (> 20.5%). The dead hearts (%) varied from 8.5 to 13.4% across cultivars and Pusa Basmati 1(13.4%) had higher damage (Table 2).

White head damage: In the reproductive phase, the white head damage was significantly higher in wet season (27.9%) than in dry season (25.6%). Si treatments had significant effect on YSB damage (20.3–30.7%) as compared to untreated control (39.4%) though the best treatment was T5-carbofuran 3G with lower per cent white heads. Among the varieties lower per cent white head damage was observed in BPT 5204 followed by KRH 2 and MTU 1010 and high damage was recorded in PB 1 (Table 2).

3.2. Studies on larval infestation

The average number of larvae dissected from base of the infested hills from Si treatments varied from 10.2 to 11.9 per four plants Significantly lower number of larvae were extracted in T5-carbofuran 3G (9.2), followed by Si treatments and the untreated control had a significantly higher larval number (12.1) (Table 2). Neither seasons nor varieties had any effect on the number of larvae in the infested plants.

3.3. Mandible wear studies

The length of larval incisors was significantly low in Si treatments (201.1–251.2 µm) as compared to untreated control (291.8 µm). Among the Si treatments, significant mandible wear was noticed in T4-RHA + imidazole (twice) followed by T3-RHA + imidazole (once), T2-Imidazole and T1-RHA. The maximum length of incisor cusps (µm) was recorded in untreated control. In the current study, varieties alone, seasons and their interactions did not have any effect on length of mandible incisors.

Table 1
Three-way analysis of variance (ANOVA) of the effect of seasons, varieties and different silicon treatments and their interactions on parameters tested under field conditions.

Sources of Variation	Dead hearts damage (%)	White heads damage (%)	Grain Yield (q ha^{-1})	Larval density (number per 4 plants)	Length of incisor cusps (µm)	Silicon content (mg g^{-1})		
						1 DBA	7 DAA	7 DAB
Seasons (S)	***	***	***	ns	ns	ns	ns	ns
Varieties (V)	**	**	***	ns	ns	***	***	***
Silicon sources (T)	***	***	***	***	***	ns	***	***
S × V	ns	ns	ns	ns	ns	ns	ns	ns
S × T	ns	ns	ns	ns	ns	ns	ns	ns
V × T	ns	ns	ns	ns	ns	ns	ns	ns
S × V × T	ns	ns	ns	ns	ns	ns	ns	ns

*Levels of significance are represented by *P < 0.05 level.**P < 0.01 level. ***P < 0.001 level and ns (not significant), 1 > P > 0.05.
DBA-Day before Si application; DAA-Days after Si application; DAB-Days after booting stage.

Table 2
Effect of seasons, varieties and different silicon treatments on yellow stem borer damage, larval density, length of incisor cusps and yield.

Treatments	Dead hearts (%) ± SD		White head (%) ± SD	Larval density (Number per 4 plants) ± SD	Length of incisor cusps (μm)* ± SD	Grain yield (q ha^{-1}) ± SD
	45 DAT	60 DAT				
Seasons						
Dry season 2011-12	7.9 ± 2.5a	11.9 ± 1.4a	25.6 ± 1.6a	11.4 ± 2.8a	242.0 ± 0.8a	20.3 ± 1.2a
Wet season 2012	10.1 ± 1.8b	13.7 ± 2.1b	27.9 ± 2.0b	11.6 ± 1.9a	244.5 ± 0.9a	12.8 ± 1.4b
Varieties						
V1- BPT 5204	8.5 ± 1.3a	10.7 ± 2.3a	23.8 ± 1.3a	10.1 ± 0.6a	244.4 ± 1.0a	12.6 ± 1.3c
V2-MTU1010	10.4 ± 2.0ab	11.9 ± 2.0ab	26.2 ± 2.0b	10.9 ± 1.0a	244.5 ± 0.9a	16.8 ± 1.4b
V3-KRH 2	10.2 ± 1.6ab	11.6 ± 1.8ab	25.9 ± 1.6b	11.1 ± 0.6a	242.0 ± 1.0a	20.7 ± 1.0a
V4-PB 1	11.5 ± 1.4b	13.4 ± 2.6b	29.3 ± 1.7d	11.3 ± 1.0a	244.7 ± 0.7a	13.8 ± 1.8c
V5- Vandana	10.3 ± 2.1ab	12.3 ± 4.3b	27.7 ± 2.0c	11.2 ± 0.8a	241.0 ± 0.6a	15.4 ± 1.5b
Silicon sources						
T1- Rice husk ash (RHA)	9.5 ± 1.3c	12.9 ± 2.4c	30.7 ± 1.6d	11.8 ± 2.3c	251.2 ± 2.0d	16.0 ± 2.0d
T2-Imidazole	7.9 ± 2.6b	11.4 ± 3.2bc	24.7 ± 2.5c	11.2 ± 1.8c	220.7 ± 3.1c	17.2 ± 1.6c
T3-RHA + Imidazole (once)	7.4 ± 1.8ab	11.2 ± 1.5bc	24.3 ± 2.2c	10.6 ± 1.5b	212.7 ± 2.6b	17.7 ± 1.1c
T4- RHA + Imidazole (twice)	7.3 ± 3.4ab	9.4 ± 1.8ab	22.4 ± 1.6b	10.2 ± 2.4b	201.1 ± 1.7a	18.7 ± 1.6b
T5- Carbofuran 3G	5.4 ± 2.5a	8.1 ± 3.1a	20.3 ± 2.0a	9.2 ± 2.0a	268.4 ± 1.6e	20.5 ± 1.5a
T6 Untreated Control	20.3 ± 2.0d	20.5 ± 2.4d	39.4 ± 1.8e	12.1 ± 1.5 cd	291.8 ± 3.0f	12.4 ± 2.0e

In columns, means followed by the same letter do not differ significantly from each other by Tukey's HSD ($\alpha = 0.05$). Each value is given upto a single decimal place.
DAT-Days after transplanting.
* Length of the incisors cusps is a mean value of N = 8 larval mandibles.

3.4. Estimation of biochemical parameters

3.4.1. Silicon content (mg g^{-1}) in the rice stem

One day before application of treatments, significant differences were observed among varieties with respect to Si content (mg g^{-1}) though Si treatments and seasons had no effect on the initial Si content in the stem. KRH 2 exhibited maximum Si content of 34. 7 mg g^{-1} and PB 1 exhibited lowest Si content (26.6 mg g^{-1}) (Table 3).

Among Si treatments, Si content in stem tissues varied significantly at 7DAA. T4-RHA + imidazole (twice) had recorded higher Si of 71.3 mg g^{-1} and T1-RHA had 46.6 mgg^{-1}. No difference was observed in T6-untreated control (29.64 mg g^{-1}) and T5-carbofuran treatments. Among varieties, KRH 2 accumulated maximum silicon content and lowest in PB 1. A similar trend was observed at seven days after application at booting stage (7DAB) (Table 3).

3.4.2. Total sugars (mg g^{-1})

Seasons and Si treatments had no effect on total sugar content in stem tissues. No significant influence on total sugars was noticed due to application of Si treatments at 7DAA and 7DAB. But mean total sugars (mg g^{-1}) content varied significantly among varieties. Total sugars within a variety did not differ between 1 DBA and 7 DAA, but there was a reduction in sugar content at 7 DAB in all the varieties (Table 2) (Fig. S1a & Fig. S1b).

3.4.3. Total phenols (mg g^{-1})

Our study reports that Si treatments did not have any effect on the stem phenol content at 7 DAA and 7DAB. However, the mean total phenol (mg g^{-1}) content in stem tissues varied significantly among varieties at 1DBA, 7DAA and 7 DAB (Table 3 and Fig. S2a & Fig. S2b).

3.4.4. Grain yield and Economic analysis

Seasons had a significant effect on grain yield. Among silicon sources, significant results were noticed with respect to grain yield. Among the treatments, T5-Carbofuran 3G recorded higher grain yield, followed by T4-RHA + imidazole (twice). Grain yield from T3-RHA + imidazole (once) and T2- imidazole was at par and a lower yield, was obtained from untreated control (Table 1). Among varieties, significantly higher grain yield of 20.7 q ha^{-1} was recorded in KRH 2 and significantly lower yield of 12.6 q ha^{-1} and 13.8 q ha^{-1} were recorded in PB 1 and BPT5204, respectively (Table 1).

Si treatments had a higher B: C ratio as compared to the untreated control. Among the Si treatments, higher benefit cost ratio was observed in T4-RHA + imidazole (twice) treatment followed by T3-RHA + imidazole (once); T2-imidazole and T1-RHA were at par. The B: C ratio of carbofuran treatment was at par with T4 treatment (Fig. 1).

4. Discussion

Silicon (Si) plays a significant role in imparting biotic and abiotic stress resistance and had a predominant negative impact on herbivore performance (Ma, 2004). The application of Si to crops is a viable component of an integrated management program for insect pests and diseases as it is relatively less expensive, leaves no pesticide residue in food or the environment, and could easily be integrated with other pest management practices (Laing et al., 2006).

It was evident from the field efficacy studies that varietal difference was observed with respect to native Si content and uptake of Si from soil solution which we observed from biochemical estimation of Si and also inherent susceptibility to YSB. PB 1 was more susceptible to YSB followed by Vandana, under field conditions. BPT 5204, KRH 2 and MTU 1010 were almost on par with each other during both seasons with respect to per cent dead hearts and per cent white heads. Earlier studies had reported PB1 as highly susceptible to yellow stem borer (Padmakumari and Pasalu, 2003). In the current study it was observed that all the Si treatments had low damage and higher grain yield.

Table 3
Effect of seasons, varieties and different Si treatments on biochemical parameters of the rice stems tissue.

Treatments	Mean silicon content (mg g^{-1})			Mean total sugars (mg g^{-1})			Mean total phenols (mg g^{-1})		
	1 DBA	7 DAA	7 DAB	1 DBA	7 DAA	7 DAB	1 DBA	7 DAA	7 DBA
Seasons									
Dry season 2011-12	29.9a	48.3a	51.9a	24.2a	24.1a	11.8a	3.3a	3.3a	2.0a
Wet season 2012	29.7a	48.8a	52.2a	24.4a	24.3a	11.2a	3.3a	3.3a	1.9a
Varieties									
V1- BPT 5204	28.2c	47.9c	50.8c	24.8c	24.3c	10.8c	2.6d	2.6d	1.6c
V2-MTU1010	32.1b	49.9b	53.8b	25.3b	25.7b	13.7b	3.7b	3.7b	2.1b
V3-KRH 2	34.7a	52.0a	55.7a	27.0a	27.0a	14.2a	4.3a	4.3a	3.4a
V4-PB 1	26.6e	45.0d	48.9d	20.7d	21.1d	10.2d	2.7d	2.8d	1.5c
V5- Vandana	27.9d	47.7c	51.2c	24.1c	24.1c	10.8c	3.2c	3.2c	2.0b
Silicon treatments									
T1- Rice husk ash (RHA)	29.2a	46.6d	51.5d	24.4a	24.3a	10.3a	3.3a	3.2a	1.8a
T2-Imidazole	29.5a	54.0c	56.1c	24.2a	24.2a	11.2a	3.2a	3.3a	1.8a
T3-RHA + Imidazole (once)	30.0a	59.9b	65.5b	24.1a	24.1a	10.5a	3.3a	3.2a	2.0a
T4- RHA + Imidazole (twice)	30.6a	71.3a	75.6a	24.1a	24.0a	10.2a	3.4a	3.2a	1.7a
T5-Carbofuran 3G	29.2a	29.7e	29.8e	24.2a	24.2a	11.1a	3.2a	3.4a	1.9a
T6-Untreated Control	30.1a	30.0e	30.2e	24.3a	24.1a	10.5a	3.3a	3.3a	1.8a

In columns, means followed by the same letter do not differ significantly from each other by Tukey's HSD ($\alpha = 0.05$).
1 DBA- one day before application; 7 DAA- Seven days after application; 7 DAB- seven days after booting; second application of imidazole at booting stage given in T4 only.

Among the Si treatments, T4-RHA + imidazole (twice) was on par with insecticidal treatment carbofuran 3G with regard to per cent damage, in terms of dead hearts and white heads and yield, suggesting RHA + imidazole (twice) can be used as an alternative for one granular insecticide application. Low damage could be due to wearing of mandibles or abrasion of gut tissue (Jeer et al., 2016). Djamin and Pathak (1967) reported that higher silicon content in rice plant imparts resistance against *C. suppressalis*. Tripathy and Rath (2016) reported that foliar application of orthosilicic acid @ 4 mL^{-1} to rice plants greatly reduced dead heart and white head damage by YSB and it also reduced its feeding. Yield levels of all the treatments were low during wet season, 2012 due to more per cent white ear incidence. The results in the present study confirm the earlier reports of Ranganathan et al. (2006), Voleti et al. (2008) and Chandramani et al. (2010).

With respect to larval density, we observed that more number of larvae were from untreated control treatment and less from T4-RHA + imidazole (twice) and T5-carbofuran treatments, which might be attributed to the increased translocation and deposition of Si in the stem tissues in each treatments. High Si content at 7 days after application (DAA), might have hindered larval entry into the stem tissues. Subbarao and Perraju (1976) also reported lowest larval survival in W1263 and TKM 6 plants treated with potassium silicate. Nozato (1982) and Ukwungwu (1984) also reported the lowest larval survival rates and larval numbers of *C. suppressalis* and *C. zacconius*, respectively, due to silicon fertilization. Kvedaras et al. (2007) reported that Si nutrition reduced the growth rate and stalk damage in sugarcane stalk borer (*Eldana saccharina*). Significant decrease was observed in borer penetration, weight gain and stem damage by *C. suppressalis* due to the

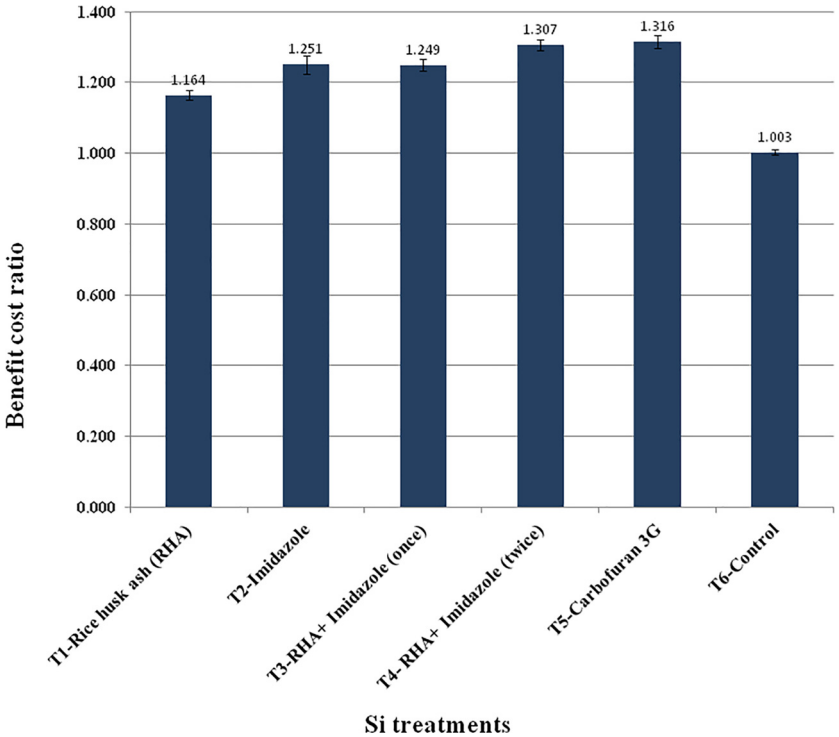

Fig. 1. Benefit: cost ratio of field application of Si for yellow stem borer management.
Note: The cost of labor for one day – Rs 300/-; Cost of RHA @ Rs 5000/ton; cost of imidazole – Rs 550/100g, Cost of carbofuran granules Rs 90/- kg and applied @33kg /ha; Cost of procurement of paddy RS 1500/- per quintal though premium varieties like BPT5204 and PB1 attract a price of Rs 1590/- and Rs 1750/-, respectively and if grown organically the price would be much higher.

application of calcium silicate @ 150 kg/ha and 600 kg/ha (Hou and Han, 2010). Similarly, application of calcium silicate affected larval survival and pupation rates in rice leaf folder, *Cnaphalocrocis medinalis* (Han et al., 2015).

In our experiment, significant reduction in length of incisor cusps of larval mandibles was observed in Si treatments as compared to the untreated control, because of mandible wearing due to feeding or boring on Si treated rice plants. It is pertinent to note that though larval density was not much affected in T1-RHA, the wearing of larval mandibles was significant. It is similar to the findings of Sasamoto (1958), Djamin and Pathak (1967) and Hou and Han (2010) who reported the defacing of larval mandibles of *C. suppressalis* due to feeding on Si rich rice cultivars. Death of larval instars of *S. incertulas* due to starvation was attributed to wearing of mandibles upon feeding on fly ash amended plants (Chandramani et al., 2010). However, either Si, or cultivar or feeding site had no significant effect on mandibular wear of *E. saccharina* in sugarcane (Kvedaras et al., 2009).

It was evident from present studies that, there was significant increase in Si content in rice varieties, upon application of RHA or imidazole either alone or in combination. Substantial research work has been carried out on the efficacy of different inorganic Si sources such as calcium silicate and calcium metasilicate (Anderson and Sosa, 2001; Keeping and Meyer, 2002; Kvedaras et al., 2007; Redmond and Potter, 2007), sodium silicate (Basagli et al., 2003) and potassium silicate (Parrella et al., 2007) on many herbivores. Being inorganic in nature, they may be detrimental, leaving residues in soil after repeated applications and in large quantities. However, use of bio-compatible organic molecules like imidazole was less expensive, and a small quantity along with natural source like RHA, would ameliorate the soils and benefit the crop as well without compromising yield penalties of biotic stress.

As the total phenol content in rice cultivars imparts resistance or tolerance towards stem borer, it is important not to disturb the phenol content of the plant. The rice varieties, PTB 33, PTB 18 and ARC 1429 which were found tolerant to YSB had higher content of total phenols and less of sugars, when compared to susceptible varieties, Jaya and TN 1 (Central Rice Research Institute, 1979). Present study revealed that there was significant difference between rice varieties with respect to total phenols content as well as total sugars content. However, in the present study no significant influence of silicon sources and solubilisers on these parameters (Fig.S1 and Fig. S2) in the stem portion of rice varieties was recorded. The TKM6 rice variety treated with organic nutrients had lowest white head damage (0.97%) which was positively correlated to the higher amount of phenol (7.80 mg g^{-1} of tissue) and Si content (6.5%) in rice stem tissues (Usha Rani et al., 2006). However, Frew et al. (2016) observed that sugarcane cane grub (*Dermolepida albohirtum*) performance was positively correlated with root phenolics but negatively correlated with root silicon as they found a negative relationship in the roots between total phenolics and Si concentration.

The beneficial effect of Si is more pronounced in biotic/abiotic stress induced conditions (Tamai and Ma, 2008). But, Johnson et al. (2017) reported that Si application in *Medicago sativa*, a legume crop increased the plant growth there by increasing the availability of essential aminoacids and thus increasing the susceptibility to sucking pest, *Acrythosiphum pisum*. Si application against biotic stresses serves as a viable component of IPM practices for pests and diseases as it is free from pesticide residue problems in food or the environment and has no cross reaction with other management practices including biological control (Malav and Ramani, 2015; Laing et al., 2006). So the beneficial effects of Si in poaceae is proven and can be well exploited but with other plant families and their pest complexes detailed studies may be essential to elucidate the role of Si in conferring pest resistance.

5. Conclusions

We conclude here that field application of a Rice Husk ash(RHA), a renewable source of Si and imidazole a Si solubiliser-cum-carrier, alone or in combination, significantly decreased YSB damage and the effect was on par with carbofuran treatment. Our field studies also indicated higher Si solubility and uptake by test varieties, no changes in biochemical parameters like total soluble sugars and total phenols content. Economic analysis of Si treatments revealed that application of RHA and imidazole was at par with application of carbofuran, a granular insecticide. RHA and imidazole could be easily used for effective, economical and sustainable management of YSB and can be integrated with other IPM practices.

From the perspective of organic farming and increased importance to organic food, the application of siliceous materials may pave the way for increasing yield and reducing the use of chemical fertilizers, pesticides and fungicides. Rice husk as an organic fertilizer, apart from increasing the productivity and water use efficiency, improved the root depth; shoot length, crop growth rate and plant height of rice plants (Ebaid and El-Refaee, 2007). RHA could be the potential source of Si as it is a major by-product from rice industries and ashes from agro industries and industrial slag also could serve the purpose. On-farm residues like farmyard manure (FYM), rice straw and rice hulls are a huge source of Si as they are repeatedly recommended for organic farming. Linquist et al. (2007) through single and multi year experiments opined that, on-farm residues could be the best option for resource-poor farmers to increase crop productivity. Aliyu et al. (2011) reported that soil amendment of rice husk powder to cowpea increased the yield and productivity and decreased the susceptibility to cowpea mottle virus. Badar and Qureshi (2014) showed that application of composted rice husk to sunflower plants significantly improved the growth and biochemical parameters as compared to control. Thus, our study indicates that application of cost effective and naturally available Si sources or materials that make Si available at very low doses can be chosen as a viable component in the management of rice pests in general and yellow stem borer in particular. In the present changing agricultural scenario wherein the cost of cultivation needs to be reduced with emphasis on eco-friendly practices of pest management, the results of the present study gain prominence and there is a great need to have a relook at the role of Si on plant growth and development and the various mechanisms that are involved in imparting resistance against biotic stresses.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.05.002.

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